APPENDIX C
The Lunar Program

INTRODUCTION

At this time in 1968, only months before the first manned mission to the Moon, it is not possible to predict a specific course of manned lunar activity in the 1975-1985 time period. So much of what we do then depends intimately on what happens between now and 1975. The factors involved include: the success of the Apollo program (defined as the first successful attempt by the United States at manned lunar landing and return); utilization of Apollo or modified-Apollo hardware in a lunar exploration program; what we find on the Moon; the usefulness of the Moon for science, space logistics operations, or lunar-based technology; the rate and manner of space technology advances; the Soviet space program; and finally, on the balance between our lunar, Earth-orbital, and planetary efforts.

We could guess at the answers to all the obvious questions and arrive at false or misleading conclusions, but it now makes sense to wait a few years for real data before focusing on any one mode of lunar activity in the post-1974 period. What can be done now, however, is to examine the options that will likely be available in 1975, predict a probable course of events within each option, determine what information would be needed to make a decision on which path to take by about 1972 or 1973, and then examine the lunar program options of the early 1970's to see if they will indeed provide the necessary information.

The approach of this paper, therefore, will be to sketch briefly the likely lunar activities for 1975-1985 using as a basis the Lunar Exploration plan and other current ideas concerning the progress of lunar activities in the 1969-1974 time period. We will concentrate, however, on the concept of a lunar base and what one might do

with such a base, since the alternative—continued multisite exploration—is largely an extension of programs of the 1969-1974 time period, all of which have been previously discussed in great detail (refs. 1 to 7).

LUNAR EXPLORATION, 1969-1974

Any program for 1975 to 1985 must build upon the program of the early 1970's, planning for which has been actively pursued by many competent groups (refs. 1 to 7). While we do not yet know in detail what that program will be, the Lunar Exploration Program Memorandum (ref. 7) indicates what is likely to occur, depending upon the level of funding, in terms of five options.

The construction of the options for the 1969-1974 time period was based upon a set of scientific and technological objectives, which we quote (ref. 7), and add to below:

The *initial* objective, which the Nation undertook with the Apollo program is to *accomplish the manned lunar landing mission.*

During this mission, the astronauts will conduct limited but significant scientific exploration, and return samples of the lunar surface to Earth.

The *next* scientific objectives which are believed achievable by the mid-1970's are:

1. Surface Features and Regional Relationships

   Investigate the form, regional setting and subsurface nature of major lunar surface features and study regional problems by landings at key sites and by extended traverses over the surface.

Of particular importance are measurements and sampling which will enable better interpretation of the recently discovered "mascons." Such information will be significant in explaining the origin of the circular mare and in determining the interior structure and thermal regime.

2. Composition of Lunar Materials

   Completely characterize the samples collected at each site and during each traverse by detailed analysis on Earth including rock identification and chemical composition.

3. Age Dating

   Establish the absolute (radiometric) ages of samples representing significant lunar events in order to obtain an "absolute" understanding of the relative sequence of events deciphered through years of Earth-based photogeology. Compare this history with that of the Earth and meteorites.

4. Internal Structure and Energy Budget

   Determine the gross internal structure and processes, ephemeris, and mass

distribution by measuring seismic activity, heat flow, gases and librations with emplaced instrumentation.

5. Lunar-wide Understanding and Geodetic Control

Survey and measure the lunar surface from orbit about the Moon, tying together studies and traverses into a regional framework, providing detailed information for science planning of surface missions, obtaining lunar-wide control of surface positions and profile, and measuring the gravitational field and local variations.

6. Interaction of Moon and Space Environment

Investigate the lunar environment, the interaction of the Moon with the solar wind, associated magnetic fields, atmospheric components resulting from neutralized solar wind, micrometeorite flux, and impact effects, by long-term monitoring on the lunar surface and in orbit.

The technological and operational objectives believed achievable by the mid-1970's as an integral part of missions directed toward the scientific objectives are:

1. Extension of Knowledge of Man in Space

Determine biomedical and behavioral performance including physiological responses and aptitudes, post-mission adaption, and increments by which mission duration can be increased. Study man-machine relationships including sensor operation, discrimination, data selection and evaluation, manual control, maintenance and repair, assembly and set-up, and mobility operations on the lunar surface.

2. Extension of Astronaut's Staytime and Mobility

Increase the ability to conduct observations and experiments on the lunar surface. Extend investigations beyond the immediate vicinity of the landing site.

3. Long-Range Surface Traverses

Extend exploration to regional problems with the capability of supporting geophysical profiles, atmospheric investigations, sample collection, and deployment of science stations along traverses.

4. Extension of Operational Techniques

Develop surface rendezvous capability. Expand manned landing capability to a significant portion of the lunar surface with long-duration mission control, inflight test and qualification of advanced systems.

5. Critical Data for Decisions on Future Uses of the Moon

Investigate techniques necessary to make man independent of Earth consumables (e.g., extraction of water, hydrogen and oxygen from lunar rocks), and to use lunar materials for construction and protection. Study the effect of lunar environment on instrumentation, and the suitability of the lunar surface (thermally and structurally) for an astronomy observatory and research laboratory.

To accomplish an effective program of lunar exploration, engineering developments and relevant scientific disciplines must be combined to achieve a series of logically interrelated investigations and missions ranging in scale from specific features to the whole Moon.

The options themselves are briefly enumerated below and shown schematically in table C-I. These program plans assume that the initial Apollo landing is accomplished with Apollo/Saturn 506. They have been structured around the baseline Apollo buy (through SA 515), with modifications introduced to meet the various substrategy requirements.

Table C-I.—*Lunar Exploration Plans*

Plan	Major components	Calendar year							
		1969	1970	1971	1972	1973	1974	1975	1976
Extended Apollo (1B)	Apollo–Post-Apollo Extended Apollo	●	●	●	●	● ●	● ●		
Early dual-launch (3B)	Apollo–Post-Apollo Extended Apollo Dual-launch (Manned orbiter)	●	●	●	●	● ●	● ● ●	○○ ○	○○ ○
Revisit (3D)	Apollo–Post-Apollo Extended Apollo Site-revisit (Manned orbiter)	●	●	●	●	● ● ●	● ●	○ ○ ○	○
Mixed (3A)	Apollo–Post-Apollo Extended Apollo Advanced orbiter Automated surface vehicle Dual-launch	●	● ●	●	●	● ● ○ ○	● ● ○ ○	○○	○○
Automated (3C)	Apollo–Post-Apollo Advanced orbiter Automated surface vehicle Particle-and-fields satellite	●	● ●	●		○ ○ ○	○ ○ ○ ○		

● Apollo/Saturn systems 506-515 ○ New systems

Extended Apollo (1B).–Continue multisite manned missions through the end of the Apollo buy of spacecraft and Saturn V launch vehicles. Introduce extended Apollo missions with increased staytime on the lunar surface, and lunar flying units for astronaut mobility after three Apollo-like missions.

Early dual launch (3B).–Introduce the dual launch in place of the last two missions in the Extended Apollo plan. This provides logistic support, the roving vehicle on the surface, and manned orbital science. This plan implies continuation of dual-launch flights, requiring a new buy of Saturn/Apollo hardware.

Revisit (3D).–Introduce the automated LM logistics carrier (LPM) by the fifth launch of the Extended Apollo plan and use the succeeding two ELM missions to revisit the LPM. This plan also implies a new buy of Saturn/Apollo hardware which will permit reuse of equipment and the conduct of preliminary baselike operations.

Mixed (3A).–Continue manned lunar exploration as in the Extended Apollo plan, adding automated support with orbital and roving vehicle missions. This plan can be continued into either a new buy of Saturn/Apollo hardware for dual-launch or mission-and-a-half mode operations.

Automated (3C).–Terminate manned exploration after four missions and continue with the automated orbital and traverse missions of the Mixed Plan. Add automated particles-and-fields satellites launched from Earth to lunar orbit.

The options of the early 1970's are in reality based on the concepts of multisite exploration and site revisit, with the site-revisit option (3D) being a type of minibase built upon Apollo-derived hardware. The site-revisit option can be looked upon as providing early experience in the conduct of lunar-base operations, but it compromises somewhat the exploration of the Moon by reducing the number of sites investigated.

A recent fiscal year 1970 submission to the Bureau of the Budget contains only three options:

Plan A: Similar to 3A, but one additional post-Apollo mission, only three ELM missions, and the dual missions moved up a year earlier to calendar year 1974.

Plan B: Three post-Apollo missions, one ELM in calendar year 1972, and dual launches in calendar year 1973 and calendar year 1974.

Plan C: Two post-Apollo missions (calendar year 1970 and 1971) and two ELM (calendar year 1973 and 1974).

Plans A and B would result in reasonable lunar program progress in fiscal year 1970, while plan C is barely a survival effort.

POTENTIAL LUNAR PROGRAM OBJECTIVES, 1975-1985

The gross options of the 1975-1985 time period will not be different from those of the earlier explorations. One can either extend the multisite exploration mode, or concentrate on establishment of a lunar base.

CONTINUED MULTISITE EXPLORATION

This strategy depends largely on the assumption that the justification for continuing lunar activity is primarily scientific—an assumption that few are willing to make. However, we cannot discard the possibility that the results from early missions will produce a strong desire to continue this mode. As such, it would be an extension of a strategy already in existence. A continuance of the multisite strategy would presumably follow along the lines discussed for the early 1970's, with the possible addition of more sophisticated hardware (e.g., self-contained, habitable, roving vehicles) and larger scientific payloads.

ESTABLISHMENT OF A LUNAR BASE

We have been asked to assume for the purposes of this study the existence of a lunar base and to show what would be done there. The assumption of the existence of a lunar base presupposes that it has been justified. Several studies (e.g., ref. 2) have been made which assumed that scientific exploration would be the justification. It is more likely, however, that science will be only one of the justifications. Other factors to be considered include technological, political, prestige, and military aspects, all of which must be dealt with in an in-depth study of a lunar base.

The establishment of a lunar base is more likely to occur if it is declared a goal of a manned space program. To be so declared, it must offer certain qualities which make it a clearly equal or

superior goal over the alternatives—those alternatives most likely being, in the 1975-1985 time period, either an Earth-orbiting space station or a manned planetary exploration.

A new NASA goal comparable to or greater than Apollo in scope must:

1. Make challenging demands that force technological advance.

The Apollo program has, for obvious reasons, focused attention on production and test. A major new program should be designed to force concentration of effort on design and innovation. Possibly inherent in this idea is the concept of a schedule of activities that does not artificially escalate costs. Consider, also, that establishment of a goal that is now completely feasible (from an engineering point of view) will not necessarily stimulate new and innovative technologies.

2. Be of relevance and exciting to the man-in-the-street.

Hit-and-run lunar exploration has only transient appeal. A continued occupation of a lunar site would represent a permanent extension of man's presence on new territory. A possible goal, which benefits by not being dead ended, is the ultimate self-sufficiency of a lunar base.

3. Offer an opportunity for accomplishment of subsidiary objectives.

In the following subsections, several of the broad categories of potential base use are outlined in a plausible chronological order of occurrence. A more detailed summary of the possible base operations, resources, and necessary developments is given under the "Lunar-Base Technological Support Operations" section of this paper (p. 39).

Continued Scientific Exploration of the Moon

By 1975, we may have detailed site information on 5 to 10 selected lunar front-side sites, solutions to some regional lunar problems based on data and samples obtained by dual-mode rover traverses, rudiments of seismic networks, a developed 10-kilometer-radius-of-action, lunar manned-mobility system (small flying unit and/or roving vehicle), and a CSM remote-sensing capability. Through use of the extended LM and/or dual-launch missions, with their associated hardware developments, staytime on the lunar surface should progress to ~12 days.

The next phase of exploration, 1975-1985, will need to establish geophysical observing stations where gaps exist in preexisting nets. This might include more front-side stations and certainly back-side stations. From a base, this will require either extensive manned/unmanned surface mobility to deploy stations (or to repair existing stations), or individual unmanned landings of automated stations. In any case, development of lunar far-side communications will be required.

The particular use of a base in geophysical monitoring would probably be in the establishment of a semipermanent observatory (remote stations for the mid-1970's are envisioned as having lifetimes of up to 5 years). Efforts to conduct high-caliber seismic studies would conceivably include layout of a LASA-type (large-aperture-seismic-array) array of stations, of short baseline, and the detonation of large explosive sources to excite the Moon artificially. Such an array of stations could alleviate the need for many individual stations.

The location of a lunar base will be determined by operational convenience and the availability of particular resources (e.g., H_2O). It is likely, however, that this area will be geologically interesting, possibly volcanic, and will afford the first opportunity for extensive investigation of a lunar "geologic" problem. This presumes that, even on the 12-day dual missions of the mid-1970's, there are insufficient man-hours to devote to EVA activity of a geologic nature. It is an established terrestrial fact that the solution of most geologic problems requires, sequentially, an initial exploration, a period of laboratory work, and a site revisit to do further experiments or collect more samples. A strategically located base provides that opportunity and, with the development of suitable mobility, actually enables one to continue multisite exploration on traverse loops originating at the base.

The concept of deep-drilling on the Moon, with coring, has been considered for at least the past 8 years. By deep-drilling we mean a minimum depth of several hundred meters. For scientific purposes, drilling is done after the delineation of problems that could be solved by drilling. This presupposes a backlog of geological, geochemical, or geophysical data at the site. With the possible exception of the site-revisit option, early-to-mid-1970 missions do not allow for that sequence of events. Deep-drilling is, therefore, an operation that would be considered at a lunar base location after extensive surface study of the complete site.

The Moon as a Base for Nonlunar Science

Besides serving as a subject of scientific exploration for its own secrets, the Moon may be an important base for outward-looking space science programs of the future.

Astronomy appears most likely to profit from lunar-based instruments. The advantages of lunar versus Earth-orbital location are discussed more fully in appendix D of this series (ref. 8). Briefly, the Moon may eventually support large optical telescopes, though the advantages of the Moon over Earth-synchronous orbits for these telescopes are not yet clear. On the other hand, there is strong evidence that the most ideal location for large radio telescopes will eventually be the rear side of the Moon. This may be the only place within our convenient reach where the Earth, which will become increasingly noisy as a radio source, may be completely screened out. In addition, the large, stable base of the lunar surface with only 1/6 g, no wind disturbance, and no atmosphere absorption, at any wavelength, are all advantageous for large radio-telescope installations. Another attractive possibility is the use of the Moon-Earth line as a radio interferometer base for highly precise directional radio astronomy. In view of the rapid growth in importance of radio astronomy and the large sums now being invested in radio telescopes, far-side lunar operations within 15 years should be considered seriously.

There are also attractive possibilities for installing large X-ray and gamma-ray telescopes on the Moon and using the atmosphere-free lunar horizon as an occulting edge that rotates uniformly about the sky (ref. 9). These, unlike the radio telescopes, need not be on the far side, since Earth noise is not a problem here.

The Moon is certain to serve as a valuable permanent base for monitoring the environment of our solar system, especially particles and fields. Solar wind, solar storms, magnetic perturbations, meteorite infall, and cosmic rays will all be worth monitoring continuously from a lunar base. This will augment Earth-based observations with data taken at a significant distance and time away from the Earth. Such data stations, strategically placed on the Moon with large separations in latitude and longitude, could probably be combined with the automated geophysical stations.

A third scientific and technological use of the Moon might be for radio, radar, and laser communications with Earth, and with spacecraft in cislunar space and on planetary missions. The lack of

atmosphere (clouds or ionosphere) at the lunar terminal will give it obvious advantages over continuous communications channels that must penetrate the Earth's atmosphere.

Use of the Moon as a Refueling and Launch Platform

Because of its low gravity, it requires 20 times less energy to escape from the Moon than from the Earth. Hence, if one can eventually generate rocket propellants from lunar resources there will be an enormous advantage in using the Moon as a supply-and-launch base for interplanetary operations. It could even be profitable to send fuel from the Moon to tanker stations permanently orbiting the Earth, for resupply (ref. 10). Because of the Moon's lack of atmosphere, one could also eventually send spacecraft back to Earth by acceleration on a long (4 to 20 miles) launch track built on the lunar surface (ref. 10). Such a launch would be efficient, since it would dispense with the large mass of propellant normally required in the early stages of rocket acceleration, and would avoid most of the gravity losses encountered in vertical launches.

Rocket propellants generated on the lunar surface could also be stored in a lunar base, both for lunar flying-vehicle operations and for abort missions back to Earth. The most probable source of rocket propellant on the Moon is water, either as liquid or ice. Once the supply is found, it would be a rather simple matter to hydrolyze the water into H_2 and O_2, which could then be liquefied for storage. The oxygen in water also has obvious utility in life support.

Return of Lunar Materials to Earth

In the first few years of lunar exploration, we can expect a steady return of scientific samples from all sites visited, for Earth-based analysis. It is possible, though it seems unlikely at this time, that there will be certain minerals in the lunar surface that are costly or impossible to prepare on Earth, even in small quantities. For example, long exposure to vacuum ultraviolet light or solar protons at the lunar surface may produce unexpected mineral forms. For these minerals, there could eventually be a useful traffic back to Earth, if Moon-to-Earth transportation becomes sufficiently inexpensive.

Construction and Processing on the Moon for Space Systems or Return to Earth

Construction of life-support bases from lunar soil or materials and assembly of large instruments and stations on the lunar surface would probably occur early in a lunar base program and will be covered in "Lunar-Base Technological Support Operations" (see below).

Probably latest in chronology, would be use of the Moon's unique environment (a vacuum of 1/6 g) to make and process materials, manufacture parts, and construct specialized hardware. The prospect of manufacturing products on the Moon for Earth use, however, appears very remote to the authors.

Because of the energy advantage in launching from the Moon versus from the Earth, heavy components for a space system that could be manufactured from lunar raw materials may eventually become one of the goals of lunar programs. Very extensive vacuum operations, such as coating large optical surfaces or preparing large solar-cell surfaces for space use could conceivably become lunar industries.

LUNAR-BASE TECHNOLOGICAL SUPPORT OPERATIONS

Mission-support facilities, materials for base construction, shelter modules, power installations, communication systems, astronomical and ecological laboratories, surface transportation and hauling facilities, propellant production, storage and fueling facilities–these and others will require extensive supporting technologies.

In this section we will briefly review some of the thought that has been given to lunar-base operations and the potential problems. Much of it is speculative, but Surveyor remote analyses and theory convince one that essential elements, construction materials, and various metals are present on the lunar surface. Their location and availability in forms amenable to concentration or processing is yet to be established; however, a good multisite exploration strategy in the early 1970's should supply the necessary information (p. 43).

ENGINEERING REQUIREMENTS

In preparing this subsection, the writers have drawn largely upon references 11, 18, 22, and 31. The subsection on the "Use and Processing of Raw Materials" (p. 43) relies heavily upon references 16, 19, and 25 for sequence and for the data presented.

Construction of a Base Station—General

The scientific mission-base requirements advanced by North American's Lunar Exploration System for Apollo study (ref. 2) define a three-phase base concept to support the scientific investigations in the 1970 to 1974 period. The first phase consists of several modules or crew shelters plus a surface vehicle. These modules would merely house three men for 3 months, and serve as a base for reconnaissance. The second phase would house six men for 3 years and serve as a center for geological, geophysical, topographic, and astronomical studies. This facility would include a laboratory-shelter module, two vehicles, and a powerplant. The third phase would provide for a dozen men for 5 to 10 years, and would have a facility that would include two shelters, an astronomical observatory, radio-astronomy facilities, and two vehicles. The entire system was proposed as feasible for the period 1970 to 1974, with support operations for this period being Earth-based.

Construction of a lunar base station will require proximity of useful raw materials, heat, water, and favorable conditions for producing and maintaining a habitable environment. Mining, processing, building, and other essential activities will depend upon numerous advantageous environmental and resource conditions. Vital to any base construction program that will depend upon local resources is the ability to excavate and tunnel, extract atmospheric gas and water, obtain working fluids, devise the means for concentrating usable raw products, and develop techniques for fabricating structural elements from environmental materials. Some of the engineering and resource considerations involved in such construction are discussed below.

Surface Mobility

The 1967 Lunar Science and Exploration Summer Study Summary (ref. 6) states that the more important recommendations

of the conference concern lunar surface mobility. It was proposed that, to obtain significant benefits from lunar-surface exploration, it would be imperative that there be a working radius of 10 kilometers. (On early Apollo missions the astronauts' on-foot radius may be about 500 meters.) Recommendations include development of manned or automated wheeled vehicles for the purpose of exploration, sample collection, geophysical studies, in situ analyses, and transportation and haulage. Such mobility devices would also be necessary in base operations and base construction.

Hall (ref. 11), in a study of the engineering implications on the Moon's surface, concludes that trafficability will be lower on the Moon than on Earth. Traction for equal-footing areas will be less, because of the relatively reduced weight, and wheel sinkage and minor obstructions may be major obstacles to vehicle mobility. To establish a basis for exploratory and construction-vehicle concepts, analyses need to be made of the characteristics of lunar-surface materials and landforms. Soil-testing techniques for use under hard-vacuum conditions will be necessary on early lunar-surface missions, to assist in the design of vehicles that will be adaptable for mobility in soft soils, on unconsolidated materials at high angles of repose, and for mixtures of rubble and finely pulverized materials.

Before haulage-roadways and surface-transportation routes may be delineated, studies are needed to determine the range in engineering properties of the surface materials for filling, grading, excavation, compaction, and cutting. These behavioral properties will have to be considered in terms of penetration-resistance, shearing strength, bearing capacity, and effective stress and dilatancy (refs. 12 to 14).

Drilling Operations

Drilling for subsurface exploration and tunneling for base installations will be early engineering problems on the Moon. NASA's Lunar Drill program has as its objective the development of a system to take core samples to at least 100-foot depth. The drill system will be required to operate in dense igneous rock, vesicular lavas, unconsolidated heterogeneous materials, and fines of varying degrees of competence. Such a drill will also operate dry, without air- or water-flushing. Westinghouse has developed a suitable rotary, diamond-core drill-bit that is operable in basalt under high-vacuum conditions (ref. 15).

Drilling and tunneling may be enhanced somewhat on the Moon because of low gravity and the existence of a meteorite-pulverized debris layer. Frictional losses will be lower, and haulage of broken rock will be easier. On solid rock, however, considerably heavier drill collars, possibly made from lunar basalt or meteoritic iron (ref. 16), may be necessary to meet required bit pressures; otherwise, drilling times will be considerably longer than on Earth. Analysis of data on drilling rates by Morlan (ref. 17), applied to probable lunar conditions, shows that a terrestrial rate of 50 ft/hr may slow to 3 ft/hr on the Moon.

Excavation and Mining

Excavation of surface materials will be an essential supporting operation for a lunar-base program; however, such excavations may be unlike conventional terrestrial methods, for as Hall (ref. 11) notes, compacting fine material on the Moon may necessitate greater applied loading than on terrestrial materials of the same density. Hall also postulates a greater angle of internal friction for lunar materials because of interlocking of the predominantly angular particles and possible high adhesion of the grains. (Analysis of Surveyor data, however, indicates that the lunar soil has an angle of internal friction and low cohesion not unlike terrestrial sandy loams.) Loose materials, for whose existence there is much evidence, could be excavated with ease.

The selection of lunar-surface mining and dredging systems has been analyzed by Schotts (ref. 18), based on such factors as environment constraints, recovery-to-waste ratio, depth and grade, and the proximity to base facilities. Among environmental problems is the high range of surface temperatures, which will require special suits for miners for day/night, light/shadow, or the use of environmental cabs. Portable structures have been suggested, from which mining may be undertaken by remote control. The lunar vacuum will present problems in the use of solid lubricants in place of the abundant grease used on terrestrial mining equipment. Nighttime mining will require much artificial lighting and a high heating load for equipment, and there will be the danger that working fluids will freeze.

Lunar mining and dredging methods are envisioned to include scraping by bulldozers, digging by shovels and draglines, and the fragmentation and scraping of materials. Irregular "ore" and terrain

profiles will likely preclude automation for all but the most simple operations.

USE AND PROCESSING OF RAW MATERIALS

Water

Green (ref. 16) believes that water is the most critical raw material for the lunar base and lists the following possible water sources: combined water in volcanic extrusives, ice in permanently shadowed zones in volcanic craters, crystallized water in volcanic sublimates, permafrost, and water in nonvolcanic rocks and carbonaceous chondrites. Of these possible sources, water is more likely obtainable from serpentine (12 percent), lavas (< 1 to 5 percent), and certain carbonaceous chondrites (10 percent). (Ruzic (ref. 19) notes that 1 percent by weight of water in the various hydrous volcanic rocks considered approximates between 1 and 2 quarts of water per cubic foot.)

On the other hand, Baldwin (ref. 20), an advocate of a Moon with a hot interior, believes that water vapor and other gases have been extruded from the Moon's interior and largely lost to space, because of the Moon's low gravity. However, water vapor may yet be evolving, and it may remain as ice in permanently shadowed zones or be trapped underground where the temperature is below the freezing point.

Hapke and Goldberg (ref. 21) suggest that the flow of low-pressure water vapor through a porous lunar soil could form permafrost at a moderate depth. If the Moon had a degasing history like the Earth, they doubt if permafrost would exist in the equatorial regions, but suggest that it is likely to occur relatively close to the surface in polar regions.

Fuels

Water is envisioned as the source of hydrogen for fuel and of oxygen for oxidizers and life support. Free water or ice, if it does occur, will be restricted to deep fractures, buried craters, debris layers, or permanently shadowed zones (especially in small areas around the poles). Interstitial free water is likely to be highly contaminated with salts and fine, particulate, mineral matter.

Schotts (ref. 22) considers subsurface mining of ice, regulated devolatilization of the frozen water and soil, and "pneumatic"

transmission of the vapor and solids to a surface vessel in which recondensed vapor would be freed of the mineral solids. Several other methods for mining subsurface lunar ice have been proposed, including Frash-type processes, circulating brines, use of nuclear reactors, and in situ hydrolysis.

Recovering water from serpentine or other hydrated minerals by a Frash-type process employing nuclear or resistance heating would be feasible if heat conductivity were good in the rock. Shotts proposes that heating serpentine to 500° C at one atmosphere would produce superheated vapor. Mining hydrated rock for surface processing would require retorting to win the water, possibly using a solar furnace.

Water obtained from lunar rocks would have to be decomposed, electrolytically, for the production of oxygen and hydrogen. The decomposition, requiring either solar or nuclear power, would be followed by liquefication for storage.

Gases

The Moon may be considered as free of any atmosphere, except for possibly a tenuous presence of water vapor, carbon dioxide, hydrogen, helium, and rare gases (refs. 23 and 24). Such rare gases are unlikely to be available to support lunar base activities, but those associated with active volcanism or which are present in thermal areas might be tapped by proper drilling techniques.

Green (ref. 25) pictures the lunar surface as mostly covered with lavas characterized by large vesicles, initially formed by entrainment of water vapor and other gases which may be recoverable by simple crushing. Although most of the gas and water vapor in the surface debris layers may have escaped, it is likely that such fluids could be impounded in rocks at moderate depth (several tens of meters). Terrestrial vesicular rocks typically contain H_20, CO_2, HC1, $C1_2$, H_2, CO, CH_4, N_2, and O_2.

Sulfur

Green (ref. 16), Ruzic (ref. 19), Schotts (ref. 22) and others have considered the possible occurrence of sulfur on the lunar surface. Shotts considers that sulfur may be present in elemental form and also as hydrated soluble sulfates, as metallic sulfides (FeS, MgS, CuS, CoS, Cu_2S_4, etc.), as well as H_2S and SO_2. Ruzic proposes that initial housing on the Moon could be in lava tubes, properly

mortared by melted volcanic sulfur, while Green, who has done extensive research in the area of lunar sulfur technology, proposes the use of sulfur as cement, sealant, insulator, construction material (mixed with ash), as a source of H_2SO_4 and of H_2S (using meteoric Ni as a catalyst), and as a working fluid in powerplants and in mineral dressing.

Using anerobic thiobacilli for the production of H_2SO_4, Green envisions the manufacture of fertilizers for hydroponic gardens, the production of explosives for lunar construction uses, and the eventual production of essential chemicals. Sulfur used as a fluid (which has a wide range in behavior and viscosities) could be employed in metal reduction, as a lubricant, and as a moderator in nuclear reactors.

Chemicals and Minerals

Alpha-particle backscattering analyses of the lunar surface material by Surveyor V, VI, and VII show the lunar soil to be similar in composition to terrestrial basaltic lava. Table C-IIa shows the Surveyor analyses in the elemental form (ref. 26), while table C-IIb is an estimate of the equivalent oxide composition, based upon many assumptions about specific elements and element ratios (ref. 27). In addition, roughly 5 percent of the meteoritic material on the Moon is believed to be of the Ni-Fe type, which typically contains about 88 percent Fe, 6 percent Ni, 2 percent P, and minor amounts of Cr, Co, etc. Only the Ni-Fe appears to be volumetrically significant.

Rubey (ref. 28) proposed that many of the elements present in terrestrial sea water were derived from fluids emanating from the depths of the Earth. Following that line of thought, Green (ref. 16) suggests that defluidization in a low-vapor pressure environment such as the Moon's would permit most gases to escape, but that Br, As, S, Se, B, I, F, Sb, Rn, Os, Cd, Hg, Pb, and Zn may be somewhat enriched on the lunar surface. Shotts (ref. 22) considers the overall lunar composition to include olivine, pyroxene, anorthite, albite, orthoclase, troillite, chromite, and apatite. He lists the following mineral groups as likely to be found on or near the lunar surface: water, hydrated silicates (chlorite, serpentine, mica, zeolites), hydrocarbons (C_2H_2, C_2H_4, etc.), carbon (graphite, CO_2, Fe_3C, $MgCO_3$, CaC_2), hydrated soluble salts (halides, sulfates, chromates, phosphates), elemental sulfur and sulfur gases, boron

Table C-IIa.—*Chemical Composition of the Lunar Surface at the Surveyor Landing Sites—Preliminary Results (ref. 26)*

Element	Chemical composition, atomic percent[a]		
	Mare sites		Highland site
	Surveyor V	Surveyor VI	Surveyor VII
C	<3	<2	<2
O	58±5	57±5	58±5
Na	<2	<2	<3
Mg	3±3	3±3	4±3
Al	6.5±2	6.5±2	8±3
Si	18.5±3	22±4	18±4
"Ca"[b]	13±3[c]	6±2	6±2
"Fe"[d]	.....	5±2	2±1

[a]Excluding elements lighter than beryllium.

[b]"Ca" here denotes elements with mass numbers between approximately 30 and 47 and includes, for example, P, S, K, and Ca.

[c]Results from Surveyor V, in this case, included both the "Ca" and the "Fe" groups. A lower limit for "Fe" was set at 3 percent.

[d]"Fe" here denotes elements with mass numbers between approximately 47 and 65 and includes, for example, Cr, Fe, Co, and Ni.

compounds, nitrogen as N_2, NH_3, TiN_3, various halides, and metallic sulfides.

Beneficiation

Developing processes for the separation and concentration of diffuse mineral materials under Moon surface conditions is a primary problem for lunar-base technology. Many concentration methods that are well established on Earth will have negligible chances of success on the Moon. On the other hand, separations which are practically impossible on Earth might be accomplished with relative ease under lunar-surface conditions.

The efficiency of most dry-gravity separation methods will be less on the Moon, where lower gravity will slow down conventional processes. Interactive forces between the surface charges on

Table C-IIb.–*Estimate of Lunar Chemistry in Weight Percent Oxides*[a] *(ref. 27)*

Oxide	Surveyor V	Surveyor VI	Surveyor VII
SiO_2	46	52.5	49
Al_2O_3	13.5	13	18.5
MgO	5	5	7.5
FeO	17.5	14.5	6.5
CaO	15.5	12.5	14
K_2O	0.5	0.5	1
Na_2O	2	2	3.5
	100	100	100

[a]Original analyses (Table C-IIa above) were in atomic percent. See references 26 and 27 for assumptions, errors, and element groupings (e.g., Na is an upper limit).

particulate materials may also seriously affect dry classification. Open wet processing, such as flotation and heavy-liquid separations, would be unsuccessful because of the high volatilization rate of liquids, according to Gaudin (ref. 29). Green (ref. 16), however, suggests that such wet processes might be practical if undertaken in an enclosed system. Such processes as leaching, amalgamation classification, and flotation, when carried out in covered vessels, could take advantage of such phenomena as a deeper nucleation of bubbles. Green (ref. 16) proposes consideration of fluid sulfur in mineral dressing techniques on the Moon, citing that pyrite, expected to be found as the stable iron sulfide on the lunar surface, would sink in 155° C sulfur on the Moon at several times the rate it would sink in water on Earth.

Electrostatic separations are seen as feasible (refs. 16 and 29), because induced charges are proportional to particle surface areas, while the weight of the particles is related to their volume.

Metallurgy

Ruzic (ref. 19) notes that lunar near-vacuum conditions might aid in the production of several metals. Refining of the base metals could be accomplished by heat alone, without reducing agents. Copper, iron, nickel, mercury, zinc, molybdenum, cobalt, and many

of the rarer metals are expected to be found in the lunar surface rocks, or in the meteorites.

A probable metallurgical attempt on the Moon will be to process naturally occurring surface rock without prior treatment. Cast basic rock (basalt) technologies have been developed in France, Germany, Poland, and Czechoslovakia (refs. 16 and 30). Czechoslovak studies indicate that the best available basalts for casting contain over 60 percent pyroxene, less than 10 percent magnetite-olivine, and about 20 percent total of nephelene and plagioclase. Green (ref. 16) suggests that basalt casting on the Moon would be favorably affected by the lower gravity, which would reduce the onset of turbulence of a specific particle size. Among the numerous proposed applications for cast basalt are construction materials, furnace materials, pipes, mill linings, tiles, bricks, ties, etc. Sintered basalt may be fabricated for tubing, bearings, wheels, furniture, axles, tools, etc. Spun basalt may be used as fabric, pads, insulation, fillers, filters, and packing.

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